2006

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Regnier, Eva D.

Elsevier

Regnier, Eva. "Doing something about the weather." Omega 36.1 (2008): 22-32.
http://hdl.handle.net/10945/65265

Available online at www.sciencedirect.com
ScienceDirect
Omega 36 (2008) 22 – 32
omega
The International Journal of Management Science
www.elsevier.com/locate/omega

Doing something about the weather☆

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Received 15 January 2004; accepted 20 July 2005
Available online 15 February 2006

Abstract

Recent developments in weather forecasting have created the potential for the operations research and management science (OR/MS) community to have a tremendous impact in distilling weather information into valuable decision tools. Weather-sensitive applications include transport, electric utilities, agriculture, and public emergency management. This article surveys existing research and practice using OR/MS tools to integrate weather forecasts in decision-making. Because the conditions that created the potential for OR/MS contributions—in particular an explosion in the amount of relevant forecast data—are quite recent, the amount of existing OR/MS work is modest. This article also describes promising but unexplored research opportunities for the OR/MS community.
Published by Elsevier Ltd.

Keywords: Weather; Decision making; Decision support systems; Dynamic programming; Stochastic programming

1. Introduction

Approximately $4T of the US economy is weather sensitive [1], and severe weather causes almost $11.2B in damage and 524 fatalities per year.[1] Not all of these damages can be avoided, but when decision makers have the flexibility to mitigate the impacts of weather, then weather forecasts can add substantial value. Industries whose assets are mobile, such as aviation, can respond to forecasts by avoiding storms. Therefore, these applications have motivated much of the development in the science of meteorology. More and more applications can now extract value from weather forecasts. Companies that are currently using weather forecasts for decision-making include SkiDoo,[2] the Indianapolis 500,[3] Union Pacific Railroads [2], Coca-Cola and Heineken.[4]

However, there is a growing discrepancy between the quality of available weather forecasts and decision makers' ability to use this information effectively. The

☆This paper was processed by Donna C. Llewellyn and Paul Griffin. It is based on a presentation at the INFORMS Annual Meeting in Atlanta, Georgia, October 2003.

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[1] Annual average over 1993–2002, NWS Natural Hazard Statistics. Damage estimate is given in 2003 dollars. http://www.nws.noaa.gov/om/severe_weather/64yrstat.pdf, accessed June 7, 2004.

[2] "Playing the weather game" *USA Today* by Del Jones, December 11, 2001, http://www.usatoday.com/money/covers/2001-12-11-bcovtue.htm, accecssed June 7, 2004.

[3] "High-tech system keeps Indy weather-informed", *USA Today*, by Gary Graves, May 27, 2004, page 3C, http://www.usatoday.com/tech/news/techinnovations/2004-05-26-weather_x.htm, accessed June 7, 2004.

[4] "Finance and Economics: a hedge against the heat; Weather futures", *The Economist*, August 16, 2003, v. 368(8337), p. 67.

0305-0483/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.omega.2005.07.011

marginal benefit of improving the use of forecasts may now exceed the marginal benefit of improving forecast accuracy [3,4]. Meteorologists have begun to exploit this potential value, often using operations research and management science (OR/MS) tools. However, meteorologists tend to view forecasting as a description of nature, rather than as inputs to a decision process. The OR/MS community's conception of uncertainty, expertise in stochastic processes, and experience working with decision-makers who are unfamiliar with probability and sequential decision-making can provide a critical link between meteorologists and the users of their forecasts.

OR/MS contributions to date and the greatest potential for impact in the future are in stochastic modeling and optimization, decision analysis problem formulation and forecasting techniques. As has been noted before, everyone talks about the weather, but no one does anything about it. The OR/MS community, keepers of "the science of better" can offer ways to do something about it.

The purpose of this article is to summarize existing research in integrating weather forecasts into decision-making and to introduce readers in the OR/MS community to newly emerging opportunities for economically and socially valuable research. Section 2 describes the culture of meteorology and recent developments in weather forecast products. The next five sections describe previous work and outline open problems with potential for important contributions by the OR/MS community in five research areas: stochastic optimization (Section 3), decision analysis (Section 4), value of information (Section 5), decision support systems (Section 6) and forecasting (Section 7). The conclusion discusses opportunities for and potential gains from collaborations between the OR/MS and meteorology communities.

2. Background

Why have these opportunities not already been exploited if OR/MS has so much to offer? The first reason is that the conditions creating these opportunities have emerged only recently. As discussed later in this section, the amount and relevance of meteorological data available has been increasing rapidly, because more observations are collected and because computer technology has allowed more detailed modeling. In addition, operational changes, such as tighter scheduling, communication technology that allows better coordination of activities, and new technologies that are more weather-sensitive, e.g. new weapon systems [5], have increased the potential value of weather forecasts.

A second reason the value of OR/MS is untapped is that there is a disconnect between meteorologists and the users and potential users of forecasts. There is still a lack of awareness in some sectors of the value of responding to weather forecasts in business decision-making. Changnon et al. [6] found that many gas and electric utility decision-makers were not aware of the existence of climatic forecasts that they said would be highly valuable to them. A similar lack of awareness has been noted in agribusiness [7,8] and in the leisure sector among others [9].

There is also a disconnect between the OR/MS community and both meteorologists and users. When OR/MS techniques such as dynamic programming have been applied to integrating weather information in decision-making, the work has been done almost exclusively by meteorologists and economists. To quote the message from the General Chair of the INFORMS 2004 Annual Meeting, "Although people from many disciplines routinely use OR, we are still in a state of affairs where scientific researchers, engineers, and others do not understand basic OR tools and how these tools can help them."[5] This article seeks to introduce the OR/MS community to our potential role so we can begin to bridge the divide.

2.1. Culture of meteorology

Meteorologists tend to view both atmospheric processes and the forecasting process as fundamentally deterministic, if incompletely known [10]. With some notable exceptions, particularly in severe weather forecasting and long-term climate modeling, meteorologists have traditionally focused on the science of the atmosphere and considered the uses of weather forecasts outside their purview [11].

Although weather is probably the context in which uncertainty is best and most widely understood, most atmospheric models do not explicitly incorporate uncertainty. Instead they are deterministic models of the physics of the atmosphere and oceans [12].[6]

Moreover, most meteorologists are well educated in physical sciences, but have surprisingly little—if

[5] Message from Manuel Laguna, General Chair, INFORMS Annual Meeting, Denver 2004, http://www.informs.org/Conf/Denver2004/

[6] This continues to be true even in models used for long-run climate forecasting. In this area, there is a great deal of research now on characterizing the uncertainty of economic and environmental inputs and outputs to these climate models [13,14].

any—formal statistics training, and usually none in stochastic modeling. Only one-third of undergraduate programs and one half of graduate programs in meteorology include a statistics course [10].

The deterministic approach has meshed well with the decision processes of many users. Weather services firm Meteorlogix tries to reduce the use of words expressing uncertainty, such as "chance" in their forecasts.[7] Pielke [15] notes that policy makers tend to seek greater certainty, rather than seeking to improve decision-making in the face of uncertainty. The attachment to categorical (deterministic)[8] forecasts is evident in the US Navy. The Navy Meteorology and Oceanography Command has a convention of issuing "stoplight" forecasts, which consist of a Red, Yellow, or Green signal indicating whether conditions will be suitable for a given mission; no quantitative probabilities or other measures of forecast quality are associated with these.[9] Although agriculture is one of the most weather-sensitive industries, Changnon et al. [8] found that agribusiness decision makers were unfamiliar with decision making under uncertainty including interpreting probabilistic statements and data quality. Even in the electric utility industry, which is at the forefront of developing methods to use weather forecasts, there is a "culture which prefers deterministic forecasts rather than probability" [16].

The decision maker has the greatest ability to optimize when he has access to all the information available to the forecaster, including uncertainty. As the weather forecasts available to users contain more complete and exact representations of meteorologists' predictions including probabilistic assessments, more and more value can be extracted by quantitatively analyzing decisions in light of weather forecasts.

2.2. Recent forecasting developments

The National Weather Service (NWS) began a major Modernization and Associated Restructuring (MAR) program in 1989, whi ch included a reorganization, a network of automated observation sites, a new generation of radar, new satellites, new models, and supercomputers [17,18]. Furthermore, both the NWS and commercial weather-service providers are issuing probabilistic forecasts instead of categorical forecasts for more events. In addition, computing power is becoming ever more abundant and less expensive, facilitating collection, dissemination and analysis of more weather information.

The availability of data to all users has expanded in part because of an expanding data collection network, including land and ship-based sensing equipment, aircraft reports and satellite imagery, which can be rapidly disseminated and integrated into forecasting models. In addition, growth in computer power and computational methods have contributed to the processing of these data and to producing more accurate and detailed forecasts. There has been an explosion of forecasting models, including dozens of global-scale circulation models, each run once to four times per day, with spatial resolution on an 80-km grid or finer and as many as 32 vertical levels. Private weather services firms interpolate from these results, sometimes integrating additional observations, to produce even finer spatial and temporal resolution. The expanding availability of data dramatically improves the potential value of weather forecasts.

Recent dramatic reductions in weather-related aviation fatalities have been attributed to improvements resulting from the MAR program [20]. The new Doppler radar can observe winds as well as the precipitation detected by previous WWII-generation radar. This has allowed improved tornado forecasting and reduction in false alarms [17]. For example, the percentage of tornados occurring during severe weather watches rose from 42% to 95% from 1978 to 1995, and lead times for severe weather warnings have increased [21,17]. Over a similar period, 72-h hurricane track forecast errors declined from a 5-year average of about 750 km to an average of about 400 km [22].

Historically, all forecasts were categorical and users did not have direct access to information about their accuracy. Recently, more weather events are being forecast probabilistically. The NWS has issued probabilistic precipitation forecasts since 1965 [4]. The National Hurricane Center (NHC) began issuing probability-of-strike forecasts for hurricanes in 1983 [23] and is currently developing a new method for generating probability forecasts; the new method will give probabilities of winds at various intensities at each geographic location [24]. The US National Oceanographic and Atmospheric Administration (NOAA)[10] Climate Prediction Center began issuing probabilistic long-range temperature and precipitation forecasts in 1994, and one NWS office has experimentally begun issuing probabilistic quantitative snowfall forecasts [25].

[7] Ron Sznaider, Vice President of Business Development, Meteorlogix, personal communication May 25, 2004.

[8] In meteorology, the term categorical is used to mean deterministic, or a forecast of only one future state [19, p. 238].

[9] Carlyle H. Wash, Chair, Department of Meteorology, Naval Postgraduate School, personal communication, April 15, 2003.

[10] The National Weather Service (NWS) is a part of NOAA.

The packaging of these data by the commercial weather services industry has also exploded in the last five years. It is difficult to measure the expansion of this industry because weather services firms are privately held, but White [26] claims, "new market opportunities for weather services are emerging at a breathtaking pace..." Currently there are 289 commercial weather services companies listed on the NWS website.[11]

Increasingly, weather services firms have developed their own meteorological models and in some cases their own monitoring networks: AWS Convergence Technologies, Inc., which is barely 10 years old, now boasts more weather monitoring locations than the NWS.[12] Another contribution of the commercial weather industry is to take government-generated data and/or models and use them to produce forecasts with finer geographic and temporal resolution, down to 1 km, and sometimes updated as often as every 20 min [2].

Commercial weather services firms can often provide forecast products that are more relevant to decision makers than those the NWS provides. They provide weather-dependent measures that are tailored to a specific industry's decision-making process, such as a modified heating degree day index for electric utilities[13] and the road speed index, which objectively reflects how weather limits driving conditions, and is used by trucking companies and public planners.[14]

Growth in financial derivatives whose value depends on weather and other contracts for exchanging weather risk also reflect the growing ability of the private sector to analyze its vulnerability to weather and climate events and manage its preparation and response.[15] The Chicago Mercantile Exchange (CME) now trades both seasonal and monthly weather futures and options that hinge on heating degree days and cooling degree days.[16] Though the market stumbled when Enron, one of the first sellers of weather derivatives, left the business, the weather risk management industry has since burgeoned, reporting a total value of contracts for April 2002–March 2003 of \$4.2B, including primarily temperature-related derivatives, as well as contracts on other weather events, including rain, wind, and snow.[17]

[11] URL: http://www.nws.noaa.gov/im/more.htm, accessed May 25, 2004.

[12] "Predicting the micro-weather", *The Economist*, v. 369(8353), December 6, 2003, p. 23.

[13] A Heating Degree Day is an indicator of the requirements for heating for a single day and is equal to the difference between the daily average and 65 °F (when the daily average temperature is below 65°) for that day. *Introduction to Weather Derivatives* by Geoffrey Considine, undated, http://www.cme.com/files/weatherde.pdf, accessed June 1, 2004.

[14] Ron Sznaider, Vice President of Business Development, Meteorlogix, personal communication May 25, 2004.

[15] Climate is simply defined as "The average of weather over at least a 30-year period." (National Weather Service Climate Prediction Center's online Climate Glossary, http://www.cpc.ncep.noaa.gov/products/outreach/glossary.html).

[16] http://www.cme.com/prd/wec/

3. Stochastic modeling and optimization

As weather forecasts become more detailed and increasingly include probabilistic information, stochastic modeling and optimization and simulation will become increasingly valuable. To date, there are few examples of such work in the OR/MS literature. However, there is already a substantial body of literature in meteorology that applies dynamic programming to the use of weather forecasts [27–30]. Kim and Palmer [31] use dynamic programming to optimize hydropower reservoir operation with respect to seasonal flow forecasts, improving annual gain by about \$1M. Bowers and Mould [32] use a combination of Monte Carlo simulation of weather conditions and a project-management model to evaluate managerial alternatives for oil platform installation projects.

Airline scheduling does make use of weather information: 70% of airline delays are attributed to weather [33]. Generally these decisions are made in response to "nowcasts"—presentations of current weather information—instead of forecasts. Forecasts and nowcasts are becoming spatially more and more refined and updates are available more and more frequently. Another recent advance is in decision support systems.

However, the use of weather forecasts for airline routing is not as sophisticated as one might expect because the Federal Aviation Administration (FAA) must approve any routing changes requested by an airline, including path changes in-flight to avoid severe weather. Perhaps because of the constraints of the existing systems, there has been little published work in airline scheduling using weather forecasts. Bertsimas and Patterson [34] optimize aircraft routing subject to dynamic weather constraints, but these constraints are known, not forecast, i.e. the stochastic updating of forecasts is not modeled. Sherali et al. [35] also take weather constraints as given before solving.

Ron Sznaider, Vice President of Business Development for Meteorlogix, which serves the airline industry, believes there is great potential for using weather infor-

[17] Weather Risk Management Association, *2003 Annual Industry Survey*, available at http://www.wrma.org

mation probabilistically for dynamic rerouting, but this would likely require technology upgrades to the FAA's system.[18] The FAA's routing system is highly complex, but is still not automated, and therefore it is currently difficult to dynamically adjust to changing forecasts.

Airlines can control some decisions that depend on weather. Leigh [36] estimates the value to Quantas Airways of a policy to carry additional fuel that would allow a flight to divert to another airport if the weather conditions at the destination airport are too poor to land. Before 1985, Quantas policy required all flights to carry this fuel [37], whereas the new policy allows the pilot to decide whether to carry the additional fuel, as long as the weather forecast meets minimum criteria. For Quantas's international flights into Sydney, the value of forecasts and the new policy was estimated at $6.9M (Australian) for 1993. However, Leigh does not analyze whether the minimum criteria for carrying additional fuel were optimally selected.

The electric utility industry has been at the forefront of integrating weather forecasts into operations and financial planning. This is partly because weather affects so many aspects of the business—demand, generation,[19] and distribution—and partly because recent deregulation and restructuring (in particular vertical de-integration) of the industry have increased the pressure to improve operational efficiency [16]. The industry has relatively well-developed models associating meteorological parameters—measured as heating degree days and cooling degree days—to its profits, via load forecasts. Forecasts are also used to plan staffing levels, for example in the electric power industry which calls up customer service personnel and dispatches line crews on the basis of severe weather forecasts [38]. In some cases the weather information and staffing software are integrated and crew distribution can be partially automated, in one case reducing staff required from 68 to 38 while reducing average power outage time [2].

One open problem for OR/MS researchers is modeling the vertically de-integrated market; there is at least one example in the literature. Kleindorfer et al. [39] model the transmission grid and short-term (e.g. pricing and contracting) and long-term (e.g. capacity investment) alternatives for generators and grid operators. Their model can be used to evaluate the financial implications of regulatory regimes and contract types from the perspectives of various market participants.

However, there is still considerable untapped value in optimizing electric utility operations with respect to probabilistic and evolving weather forecasts: a 2002 workshop that brought together representatives from the electric power industry and the meteorological sciences, reported that "the industry needs to cultivate a culture that can utilize probability in decision-making and...develop business tools to use probabilistic forecast information," and emphasized that "decentralized stochastic optimization" for operations planning was key [16]. Load forecasting models could benefit from stochastic elements: the Tennessee Valley Authority uses a neural network for load forecasting, but the temperature forecasts used are deterministic.[20] Other open research areas for stochastic optimization in electric utility planning include: design of forecast variables, including measures of uncertainty, tailored for electric utility business models; design of mechanisms for demand side management, i.e. inducing conservation and on-site generation by customers; and game-theoretic modeling and contract design for vertically de-integrated generation, transmission, and distribution firms [16].

Agriculture is one of the most weather-sensitive industries. Although there is a considerable literature (cited in the next section) that uses dynamic programming to estimate the value of weather forecasts for agricultural decisions, there is no evidence in the literature that the industry uses stochastic optimization techniques in decision making. The optimal policies developed in academic studies are rarely implemented because these decision-analytic models are generally too simple to adequately represent farmers' true decision context.[21] OR/MS practitioners and researchers have more experience with these tools and can take these approaches to another level, more fully utilizing the available information and developing more sophisticated models.

Many other industries can also manage production and inventory planning as a function of weather-dependent demand. Retailers can use forecasts to project demand for weather-sensitive items, such as iced tea and snowmobiles. A UK industry survey found

[18] Ron Sznaider, Vice President of Business Development, Meteorlogix, personal communication May 25, 2004.

[19] For example, hydropower. See summary of Kim and Palmer [31] above.

[20] "Doing something about the weather", InsideTVA: A Monthly Publication of the Tennessee Valley Authority by Myra Ireland, January 2003, http://www.tva.gov/insidetva/jan_03/, accessed May 25, 2004.

[21] Rick Katz, Environmental and Societal Impacts Group, National Center for Atmospheric Research, personal communication, March 7, 2004.

that 20% of surveyed businesses had experienced surplus or stockouts due to demand changes caused by weather [9]. Staff scheduling is another aspect of production that can be planned in response to forecasts. Advance crew call-ups on the basis of weather forecasts are critical in snow-removal operations, and are sensitive to accurate accumulation predictions, but currently any optimization of these decisions is manual [40]. Optimizing the use of weather derivatives is another potential research area for financial OR. Munich's Oktoberfest,[22] Coca-Cola and Heineken all hedge against adverse weather.[23]

In an example of the value that can be added by stochastic modeling, Regnier and Harr [41] have developed a Markov model for hurricane evolution, based on a NHC climatological hurricane database, and integrated this with a simple cost:loss decision model to reframe hurricane preparation as an optimal stopping problem. The Markov model is less accurate and precise than the highly dimensionalized, but deterministic meteorological models that are used to produce forecasts. However, the meteorological models do not include uncertainty explicitly and can only add uncertainty by using simulation. The Markov model allows for dynamic optimization, and also for an estimation of the value of waiting for updated forecasts before undertaking costly preparation actions. The value of waiting is related to the financial concept of option value and can be used to approximate optimal dynamic decisions in real-time decision-making, as a supplement to storm track forecasts based on deterministic atmospheric models and probability-of-strike forecasts based on historic errors. The value of modeling flexibility is substantial, and this model can also be used for strategic decision-making, for example to estimate the value of investments to reducing preparation times.

4. Decision analysis

Decision analysis also has a broader role in formulating problems to take advantage of meteorological information. By integrating weather forecasts with business operations and planning models, decision analysis can increase the value of existing forecasts and guide the design of forecast products [42]. Decision analysis could even inform meteorology research directions by identifying which weather parameters—such as spatial resolution, accuracy, or lead time—would add the most marginal value if improved.

An important example of this is the work for the Intergovernmental Panel on Climate Change in developing frameworks for characterizing uncertainty in climate systems, in economic systems, and in their interaction in order to support policy decision-making [13,14]. Lempert et al. [43] describe a new framework for approaching uncertainty in the climate and economic systems to help identify the key uncertainties and identify policies that are robust to the unresolved uncertainties. This provides a constructive alternative to a paradigm in which certainty, or probabilistic descriptions of uncertainty, are sought as a precondition of policy decisions.

The process of formulating a problem in a decision-analytic framework in itself can add substantial value by highlighting relationships that are not necessarily evident to users or forecasters. For example, Sonka et al. [30] use a corn-production decision model to illustrate the value of modeling flexibility and in particular modeling sequential inter-dependent decisions. Mjelde and Dixon [44] use a dynamic programming model of corn production to examine the relationship between the economic value of climate forecasts and the forecast lead time. They demonstrate that the marginal value associated with additional lead time is overestimated if the model does not allow the user to anticipate future forecasts.

Modeling the consequences of decisions can illuminate critical decision variables, critical thresholds where more information can be most valuable, and critical trade-offs—such as the trade-offs between lead time and forecast accuracy. For example, in the Louisiana Department of Transportation sets a 39 mph wind-speed threshold for closing down operated bridges, such as drawbridges. This threshold is not set according to the maximum safe wind speed; instead it is an artifact of the NHC's forecasting format: the NHC predicts the extent of wind speeds of 39, 54, and 74 mph or greater.[24]

The cost of civilian evacuations is usually estimated at approximately $1M per mile of coastline evacuated [45], but may be as high as $50M in some areas [46]. Although hurricane evacuation guidance generally treats the evacuation decision as a static Go/No-Go decision, planners have some flexibility, for example, they may be able to reverse traffic flow, partially evacuate only

[22] The New York Times, August 15, 2003 Section W, p. 1, Column 3, "Letting Nature Run Its Course, and Making Money From It" by Heather Timmons.

[23] "Finance and economics: a hedge against the heat; Weather futures", *The Economist*, August 16, 2003, v. 368(8337), p. 67.

[24] George Gele, Architect/EOC Coordinator, Louisiana DOTD, personal communication, May 27, 2004.

the most vulnerable areas, and recommend "sheltering in place" instead of evacuation. Regnier and Harr [41] show that modeling these alternatives and reframing the decision as an optimal timing of evacuation problem adds value and illustrates the trade-off between early, inexpensive preparation vs. better forecasts available later in the storm.

Decision analysis has a role in integrating weather forecasts with business operations and planning models. For example, weather services firm Meteorlogix has a professional services group dedicated to tailoring weather products to specific users' business models. The majority of this group are non-meteorologists whose expertise is in working with industry.[25] There have been repeated calls for greater analysis of the uses of weather forecasts and for more communication between the users and the producers of meteorological data from within the meteorology community [11,47,48] and interdisciplinary collaboration [42]. A recent report on guiding principles for the US Navy Meteorology and Oceanography Command emphasized the importance of a "business model", i.e. an understanding of the costs of uncertainty about weather on particular missions [5].

5. Value of information

The OR/MS concept that is best known in the meteorology community is the value of information. In the past 10 years, budget-cutting pressure has prompted government-funded meteorologists to ask what is the economic value of their output in order to justify their operating budgets [37,49]. New Zealand has gone so far as to privatize its weather service [26], and the United Kingdom has moved in that direction. The US Navy's Meteorology and Oceanography Command has an initiative to measure the operational impact of its forecasts, both in order to substantiate the value it provides and to help focus attention on improvements that would offer the most value; the Air Force Weather Agency has similar efforts under way.[26]

A number of meteorologists advocate the use of decision-analytic approaches to value instead of economic methods such as stated preference or willingness-to-pay [11,42,50]. A decision-analytic framework has already been used extensively in the meteorology literature to estimate the economic value of existing weather forecasts and hypothetical future forecasts [28,36,42,51–53]. For example, Considine et al. [54] use a prescriptive decision model, industry cost data, and historic storm and well data, to estimate the value of current and hypothetically improved hurricane forecasts to owners of oil wells in the Gulf of Mexico.

There have been many studies of this type in agricultural applications. The decision contexts that have been analyzed range from short-term (e.g. frost protection, application of herbicides and fertilizers) to long-range (e.g. decisions regarding which crop to plant) and long-range financial planning (hedging weather-related risk with crop or weather derivatives) [1]. Mjelde et al. [55] survey studies of the value of climate forecasts in agriculture. Adams et al. [52] use a plant-growth model together with historical climate data in a decision-analytic framework to estimate the value of hypothetical, improved forecasts for El Niño to be $145M for perfect information, and $96M for a lesser improvement in accuracy. Brown et al. [28] present another dynamic optimization problem for wheat farmers. They find that forecasts that are only slightly more accurate than the historical average (climatological) forecast lead to a change in the optimal policy.

Whereas most of the decision analysis studies in the meteorology literature are prescriptive, Stewart et al. [40] use a descriptive model of the decision-making process in their case study on the use of forecasts in snow removal decision-making on the New York State Thruway. The difficulty in gathering the data necessary to model the decision process, the weather-forecast system and the consequences of decisions prevented the authors from arriving at an estimate of the value for existing or improved forecasts.

Estimates of the value of future, improved meteorological services have also been used to justify investments in new data collection, computing, and regional presence infrastructure. For example, NOAA commissioned a cost:benefit study to quantify the benefits of current NOAA weather forecasts and the benefits to be derived from improved forecasts expected to be produced by a new supercomputer [56]. The Office of Naval Research and NOAA commissioned a study of the economic impacts of a proposed integrated ocean observing system [57].

Decision-analytic approaches to the valuation of weather forecasts have also been adopted by the meteorological community in their search for forecast quality measures. Despite previous research showing that statistical measures of forecast quality are not tightly linked to economic value to users [58,59], meteorologists generally use statistical measures of quality.

[25] Ron Sznaider, Vice President of Business Development, Meteorlogix, personal communication May 25, 2004.

[26] R.D. West, Oceanographer of the Navy, *Naval Oceanography Program*: *Operational Concept*, Office of the Oceanographer of the Navy, March 2002.

6. Decision support systems

In addition to estimating the value of information, OR/MS can enhance forecast value by designing decision support systems and distilling the vast quantities of meteorological data now available into a useful format. The National Academy of Sciences [18] predicts that "the familiar weather forecast products will be augmented, or even superseded, by information in the form of decision-support aids tailored for business, public, and personal decisions." To date, these have been designed without OR/MS involvement. However, OR/MS is uniquely placed to contribute to such efforts because of our experience working with industry, and our expertise in behavioral decision analysis and in modeling and working with complex systems.

There are many recent examples of decision support systems developed to enable users to extract more value from existing data by researchers outside the OR/MS community. The National Center for Atmospheric Research is developing a Weather Support to De-Icing Decision Making support system to display various data relative to aircraft icing. In demonstration, this system saved an estimated \$1M per year at LaGuardia airport and \$2M per year at O'Hare [60]. In collaboration with the airline industry, NOAA developed a forecast product that includes probabilistic forecasts, designed specifically for the industry's needs in responding to severe weather [33]. In addition, the trend is for air traffic controllers and dispatchers to have a single display that integrates aircraft situation data (location, trajectory) with weather data layers, whereas in the past there were multiple separate displays.[27] The Louisiana Department of Transportation and Development (LADOTD) is currently creating data-collection and dissemination systems to support road and bridge-closing decisions and the decision to reverse traffic flow during hurricane evacuations.[28] Meteorlogix is enhancing the products it currently provides public safety officials, which have previously communicated severe weather information, by integrating a plume dispersion model that can aid in monitoring the path of accidental or terrorist releases of chemicals or other dangerous substances.

Even in the electric utility industry, most weather-related decisions are not automated [2]. However, the National Severe Storms Laboratory of the NWS collaborated with a power and water utility to develop ways to exploit improving weather information. A primary component was improved displays of critical weather information, both forecast and real-time [38].

Carr et al. [61] developed a decision support system currently used by tropical cyclone track forecasters in the North Pacific. It is an expert system that presents multiple storm tracks based on different physical models. It identifies models that show patterns that have previously characterized large track errors, and flags these models. The forecasters use this information, together with other information, to make a decision as to whether to exclude the model's track from the consensus (average) track typically issued as the official forecast.

7. Forecasting methods

The OR/MS community can offer a diversity of forecasting methods that will supplement meteorology's generally deterministic approach in the ongoing development of weather forecasting techniques. Stochastic modeling, and even time-series statistical methods can improve probabilistic forecasts and retrospective understanding of error. For example, Hughes et al. [62] develop a Markov model to simulate precipitation. Abramson et al. [63] develop an expert system based on a belief network to predict severe weather in Northeastern Colorado. Wilks [64] presents a method for assessing continuous probability distributions of temperature and precipitation from probabilistic but categorical forecasts issued by the NOAA Climate Prediction Center.

The explosion of data availability has also created a niche for data-mining and data-assimilation methods. For example, the electric power industry could benefit from a neural network or other method to integrate Doppler weather data into demand forecasting [16]. Hall et al. [65] use a neural network to develop probability of precipitation forecasts and quantitative precipitation forecasts, with excellent results.

Perhaps the most important current opportunity for contribution in forecasting is in combining multiple forecasts. In tropical cyclone forecasting research, there is a considerable amount of current work on combining forecasts from multiple experts, i.e. different atmospheric models, as well as multiple forecasts generated by simulation using a single atmospheric model. There has been little, if any, cross-fertilization on this topic between the OR/MS and meteorology communities. Goerss [66] reviews the meteorological literature on consensus tropical cyclone forecasts, and de Menezes et al. [67] review OR literature on combining forecasts.

[27] Ron Sznaider, Vice President of Business Development, Meteorlogix, personal communication November 17, 2004.

[28] George Gele, Architect/EOC Coordinator, Louisiana DOTD, personal communication, May 27, 2004.

Currently, tropical cyclone forecasters use a simple average of the storm track produced by multiple models as the consensus track, as for example in the decision support system for tropical cyclone forecasters developed by Carr et al. [61]. The purpose of the consensus track is to improve accuracy, not to measure uncertainty. Though forecasters understand that the divergence among multiple models is related to the predictability of a given storm, no probabilistic information is extracted from multiple forecast tracks. Multiple tracks are weighted in the consensus average only in that one or more tracks may be eliminated from the selective consensus track before averaging. There are no automated methods to weight models' forecasts according to indicators of their performance for a given storm, or for past storms. Carr et al. have identified, based on historical performance, indicators of problems with various models, and their decision support tool flags these indicators for the forecaster, who makes the decision as to whether to screen out a given model's forecast track.

The second half of the problem of combining tropical cyclones forecasts is integrating ensembles of forecast tracks which are used to generate probabilistic forecasts in essentially a Monte Carlo approach. Uncertainty is introduced by perturbing the initial conditions to create ensembles of simulation runs [68]. Ideally, it would be possible to combine the uncertainty information contained in the divergence among atmospheric models as well as the chaotic uncertainty modeled with simulations. Good probabilistic forecasts for tropical cyclones would be very valuable for decision making, as hurricane preparations and the consequences of inaction are very costly, as discussed above. This is an important and rich area of current research.

8. Conclusions

Recent improvements in meteorological science and forecasting have dramatically increased the potential value of weather forecasts in many application areas, including transport, agriculture, power generation and public emergency management. Even within the meteorology community it has been argued that advances in atmospheric science have outpaced the development of the ability to use the science effectively [49] and that improving the communication of meteorological information and tailoring meteorological products to users' decision contexts currently have much greater marginal value than further refinements in the science of meteorology [3,4].

The OR/MS community is ideally placed to contribute to the exploitation of this new value: we have experience in quantitative modeling of public and industrial decision-making using complex information, and in modeling and optimizing stochastic systems. Because of the lack of contact with the meteorology community and because the opportunities have only emerged recently, the OR/MS community has contributed relatively little to the appropriate exploitation of meteorological information to date.

This paper has reviewed OR/MS work to date in integrating weather forecasts into decision processes, and has described several open and potentially very rewarding areas for further OR/MS research. There really is a $20 bill lying on the street, but only a person—or group of people—familiar with both the potential applications and meteorology can pick it up.

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